CALCULATION OF PROCESSES FOR CANNED FOODS

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Calculation of p

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2. data analyzing
3. cooling curve
4. heating products
5. can size conversion

American Can Company

Technical Service Division Memorandum

CALCULATION OF PROCESSES FOR CANNED FOODS

MAYWOOD, ILLINOIS

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FOREWORD

The mathematical analysis of thermal processes for canned foods is well covered in the scientific literature. The bibliography at the end of this memorandum covers published work on this subject through the last three decades, which period covers practically the whole life of the subject. This literature is not always accessible to a technologist interested in this subject. It is for this technologist that this paper is prepared. An effort is made to present the information necessary in the calculation of thermal processes without concern for the precisely accurate theoretical considerations found in the literature. More often than not, these serve only to confuse the issue for the man not especially trained in those sciences, who is only searching for the final answer - process time or sterilizing value, whichever the case may be.

Introduction

It may be well to state at the outset, that, for a given set of conditions, such as the temperature at which processing is to be accomplished, the process time and the sterilizing value are dependent variables, that is, the value of one is dependent on the other and each can vary over wide limits. It is obvious, therefore, that one cannot be determined without knowledge of the other. This should not deter us, however, because commercial experience for several decades has been such that there is available an effective yardstick of one variable or the other which can be used to measure the requirements for some new condition to be determined. Saying this in specific terms, commercial experience with cream style corn is such that one may place considerable confidence in a process of 90 minutes at 240°F. for a #2 can when the initial temperature is 180°F. This immediately gives a standard of comparison for other conditions. It might also be said that over a period of years uncured meat has been successfully canned when processed to a sterilizing value of 6. This value can therefore be used as a yardstick in measuring the process time for canned meat for any particular set of conditions.

With this in mind, the technologist is now ready to enter into the mechanics involved in the determination of sterilizing values or process times. For one having a resonable faculty for handling algebra and logarithms it will not be difficult to carry out the necessary calculations.

Heat Penetration Measurement

To determine the heat penetration curve it is necessary, of course, to have the equipment to measure temperatures in the slowest heating portion of the can during a test heating period. This is highly specialized equipment and usually it is not practical for small packers or canners to acquire such equipment.

Suffice it to say here that the heat penetration curve is determined by inserting a thermocouple into the slowest heating point of the can and observing the time and temperature characteristics during a test cook. A thermocouple is a junction of two wires made from different metals which has the property of developing low voltages to a degree dependent on

the temperature. By means of an instrument called a potentiometer, these voltages can be measured and converted to degrees of temperature. This conversion is usually done automatically by the dial of the potentiometer which is so calibrated by the manufacturer. Therefore, the equipment necessary for a heat penetration test includes one, or preferably more, thermocouples, stuffing boxes for entering the can and retort, selector switch when more than one thermocouple is used, and a potentiometer.

Methods of Analyzing Data

Let us assume that you have acquired data from a heat penetration test and are ready to proceed with the next step. There are three methods that may be used in analyzing the data which are:

1. The graphical method, or the method of Bigelow.
2. The formula method, or the method of Ball.
3. The nomogram method, or the method of Olson and Stevens, and Roberts.

These three methods are based on identical principles, but the mechanics or procedure of the method is different in each case. Each method has its own advantages, and, in general, the choice of methods may be governed by the following conditions:

Use graphical method 1. when it is desired to measure the absolute sterilizing value in a particular test when such conditions as come-up time, cooling water temperature, or the holding time after processing but before water cooling, are different from normal. This method is also adapted to the case when the heat penetration curve cannot be represented by one or two straight lines on semi-logarithmic paper within the lethal temperature range. It is not readily adapted to the calculation of processes when the retort temperature or initial temperature is different from those under which the heat penetration curve was obtained.

Use formula method 2. when the heat penetration curve can be represented by not more than two straight lines on semi-logarithmic paper and certain conditions bring the problem outside the scope of the nomogram method 3. These certain conditions will be obvious if the nomogram method is tried and some values fall off the scales.

The nomogram method 3. is recommended for all standard calculations involving a heat penetration curve represented by not more than two streight lines on semi-log paper in

the lethal temperature range. If it is discovered by trial that conditions are such that the problem is outside the scope of the nomogram, method 2. must be used.

Each method will be described in detail and it is believed that, with a little practice, the technologist will be able to use any of the three methods with ease.

The Graphical Method, or the Method of Bigelow

It is first necessary to set up a standard of sterilizing value. This is conventionally done by establishing 250°F. as the reference temperature and establishing the lethal heat in terms of minutes at 250°F. Of course, other temperatures also have lethal values. It has been found that 1 minute at 250°F. is about equal to 10 minutes at 232°F. or 100 minutes at 214°F. Stated mathematically the sterilizing value (F_o) temperature (T) relationship is:

$$F_o = \frac{t}{\log^{-1} \frac{(250-T)}{(18)}} \quad \text{or} \quad t10^{\frac{T-250}{18}}$$

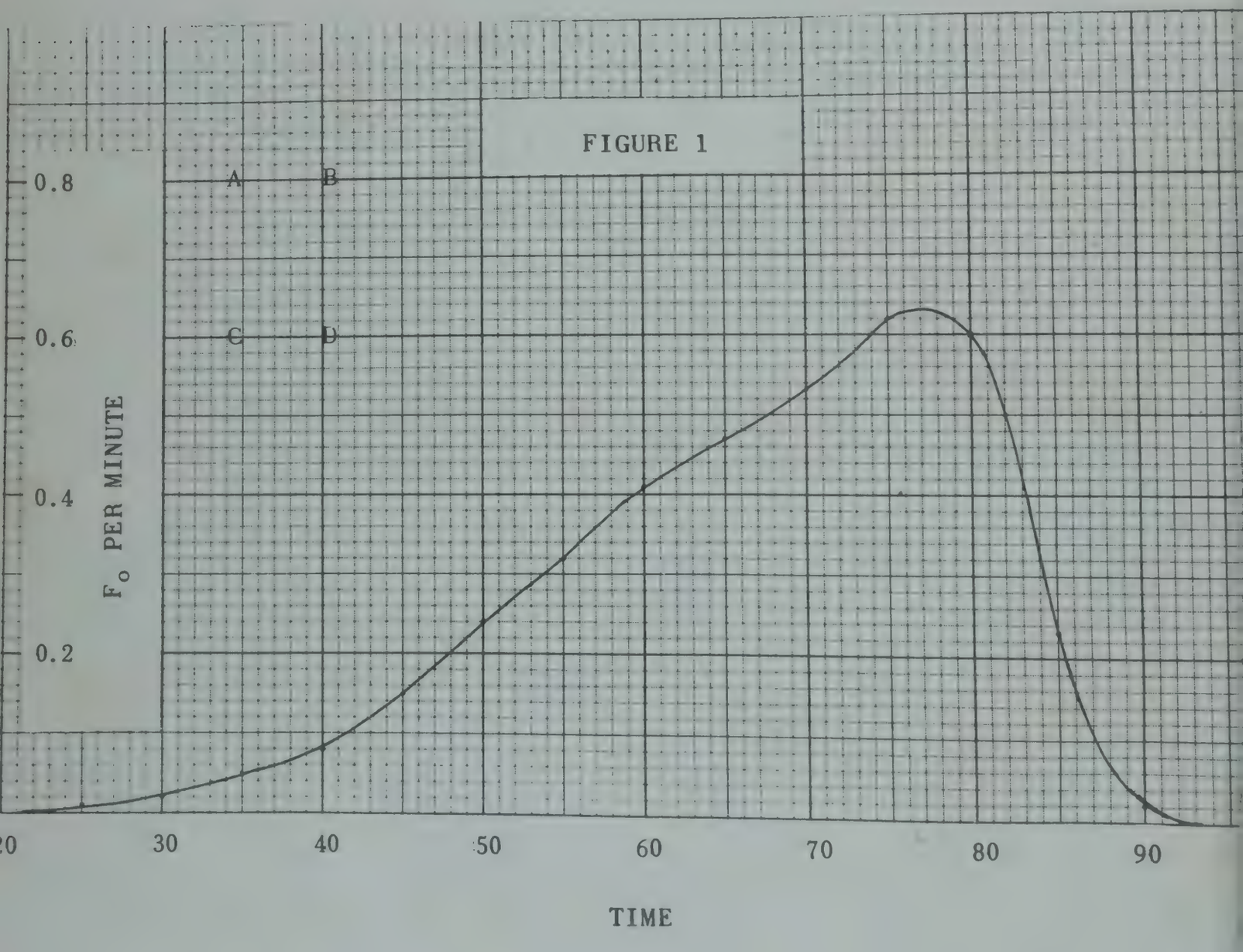
where t is the time held at temperature T.

Now the heat penetration data, as usually obtained, are in two columns showing the temperatures corresponding to given times, as indicated below. Adjacent to this, has been constructed a third column which will be called the sterilizing value effective in 1 minute at the temperature indicated. For example:

Heating and Cooling Data

Time Minutes	Temperature °F.	$10^{\frac{T-250}{18}}$
20	208	0 (approx.)
25	214	.01
30	220	.02
35	226.5	.05
40	230	.08
45	235	.15
50	239	.24
55	241	.32
60	243	.41
65	244	.47
70	245	.53
75	246.5	.62
80	246	.60
82	244.5	.50
85	238.5	.23
90	220	.02
95	205	0 (approx.)
100	193	0 "

It will be noted that temperatures less than 214°F. are ignored as these temperatures provide less than 1% of an Fo unit for each minute which, for practical purposes, is not worth considering. It will also be apparent that the sum of the Fo values in the third column would be the sterilizing value of the process if a temperature observation had been made each minute of the process. A curve, called a lethal rate curve, can be plotted showing the relationship of Fo with time which is shown in Figure 1.



Because the vertical distance on this curve represents the Fo effective for 1 minute, it is easy to see that the total sterilizing value is equal to the sum of all the vertical

distances for every minute of the process. In other words, the sterilizing value is proportional to the area under the curve. Thus, it is necessary to measure the area under the curve in order to determine the sterilizing value. This can be done by the rather laborious method of counting the small squares. A faster way is to calculate the area by utilizing Simpson's rule for measuring irregular areas. While this rule may be well known to mathematicians, it is not so well known to others and so will bear repeating:

Simpsons Rule

> "Divide the area into an even number of panels by means of vertical parallel lines spaced equidistant from one another. The first and last of these lines called the extremes may be zero length. The area will then be found by measuring the lengths of the vertical lines and adding to the sum of the lengths of the extremes, four times the sum of the odd numbered lines between the extremes and twice the sum of the even numbered lines between the extremes and multiplying the whole sum by 1/3 of the distance between the lines."

Refering to Figure 1 the length of the vertical lines will correspond to the value of $10^{\frac{T-250}{18}}$ shown in the third column of data on page 3. If an even number of panels each five minutes wide are to be taken, the extreme ordinates will be, in this example, those existing at 20 and 100 minute time values.

The sum of the extremes is of course zero.

Four times the sum of the odd numbered lines is:

$$4(.02+.08+.24+.41+.53+.60+.02) = 4 \times 1.90 = 7.60$$

Twice the sum of the even numbered lines is:

$$2(.01+.05+0.15+ .32+.47+.62+.23+0) = 2\ (1.85) = 3.70$$

$$F_o = 5/3 \times (7.60+3.70) = 18.83$$

Note that application of Simpsons Rule requires that in this example the lethality measured at 82 minutes or any other value between even increments be ignored. The vertical lines are numbered consecutively from the first extreme to the last odd numbered line giving insignificant lethality. The lines must be equidistant apart.

It may be more accurate to measure the area under the curve with an instrument called a planimeter. The area so measured will be in square inches which must be multiplied by a

factor to convert it to F_o units. This factor is found by determining the area of a unit sterilization area such as ABCD in Figure 1. Note that the product of the height and width of this area in terms of F_o per minute and time is unity. The factor to be multiplied by the square inch area of the lethal rate curve is the reciprocal of the square inch area of the unit sterilization rectangle.

You will undoubtedly agree that this procedure, while rather long, is simple enough. The procedure for determining the length of the process for a known sterilizing value is quite similar except, instead of measuring area for a known length of process, a process is found to yield a known area under the curve. For example, suppose a process is wanted having a sterilizing value of 10, previous experience having shown that this value gave satisfactory results. It is necessary then to find a time that would yield an area of 5 square inches under the lethality curve. Inspection of the curve would lead us to believe that this time would not be far from 65 minutes. We will, therefore, estimate a cooling curve from 65 minutes which we can do fairly accurately by drawing it parallel to the actual cooling curve from 78 minutes. Now, we will measure the area under this 65 minute curve by one of the methods previously described, and we find it to be 4.56 square inches. Since this process fails to give us 5 square inches, or 10 F_o units under the curve, we know that 65 minutes is not quite enough. Actually we need go no further than this as it is almost a certainty that the next higher practical process, i. e., 70 minutes, would yield at least 5 square inches. We check this though and find the area under the 70 minute curve to be 5.85 square inches or 11.7 F_o units. We could, of course, interpolate between 65 and 70 minutes to get a more exact time, but for practical purposes we would select 70 minutes.

It should be emphasized again that the results obtained by this method are valid only when the initial and retort temperature conditions are the same as those of the heat penetration tests. If the heat penetration curve can be represented by a single straight line on semi-logarithmic paper, it is possible to make corrections for these factors but, in this case, the graphical method is not the recommended one. Either the formula method or the nomogram method is better suited to the calculation.

A special graph paper to expedite the plotting of the lethal rate curve has been prepared by Schultz and Olson (See 1940 reference).

The Formula Method, or the Method of Ball

The procedure in calculating by this method requires heat penetration factors as derived from a semi-logarithmic heat penetration curve. The first step is to plot the heat penetration data so that the coordinates are time and the logarithm of the difference between the retort and can temperatures. The plotting will be expedited if semi-logarithmic paper is available; thus, time can be plotted as abscissae and the number of degrees below retort temperature as the logarithmic ordinates. Having done this, it is necessary to determine the slope and lag factor, which describe the heat penetration curve for most canned products. Certain non-homogeneous products or non-viscous fluids will show a change in the rate of heat penetration after heating for a certain period and, if this occurs, the time of change and the new slope must be determined.

A typical semi-log heat penetration curve is illustrated in Figure 2, appended. Not more than two straight lines are drawn through the points in the lethal temperature range (above 210°F.). An attempt should be made to pass the straight lines within one degree of all the points rather than to fit them by any geometric mean method. Having fixed the position of those lines, the factors must be determined, such as points and slopes, that establish the curve in relation to the initial temperature and retort temperature. Some curves will not exhibit a change in slope so only the slope and lag factor will be necessary; other curves will exhibit a change in slope and then the second slope must be determined, as well as the time or temperature at which the change occurs. The symbols for the factors describing the heat penetration or heating curve are shown in Fig. 2 and are also listed in the appendix.

Now in making a heat penetration test, or in any process for that matter, some time is required in bringing the retort to processing temperature. It will be obvious that the "coming up" time does not have the heating value of the holding temperature, and it will also be obvious that its heating value will be more than zero minutes. Conventionally, the heating value of the come-up time is taken as 0.4 of the come-up time. This means that the corrected

beginning of the process in the curve illustrated (See Figure 2) is not when the retort reaches 240°F. but 8 x .4 = 3.2 minutes before steam-up time. The time and temperature values are taken from this point, that is, the origin of the straight line with the corrected beginning of the process, which in this example is 110 degrees below retort temperature; the change in slope occurs 14.8 minutes after the corrected beginning of the process. It is a good idea always to make this correction because retort come-up times will vary over wide limits and, unless means are provided for correcting these to zero, the come-up time would always have to be specified with the heat penetration curve. If, in calculating a process, one wants to make allowance for the come-up time, it is a simple matter to subtract 0.4 of the come-up time from the calculated process, or if the F_o is the sought unknown, 0.4 of the come-up time should be added to the given time.

The equations involved in calculating the process time (B_B) or the sterilizing value (F_o) of the given process when the heating curve does not exhibit a change in slope are as follows:

1. $F_o = \dfrac{f_h}{(f_h/U)\ Fi}$

2. $B_B = f_h\ (\log(jI) - \log g)$

When the heating curve exhibits a change in slope the following equations are used:

3. $F_o = \dfrac{f_2}{(f_h/U_{h2})\ Fi} \quad - \quad \dfrac{r_{bh}\ (f_2 - f_h)}{Fi\ (f_h/U_{bh})}$

4. $B_B = f_h \log(jI) + (f_2 - f_h) \log g_{bh} - f_2 \log g_{h2}$

The solution to these equations is accomplished by substituting the proper values of the indicated terms. The values for these terms are determined as described below:

f_h - from the heat penetration curve (see Fig. 2).

f_h/U (equation 1) - from Fig. 3 (attached) for the value of log g as determined by this equation:

$$\log g = \log jI - \frac{B_B}{f_h}$$

Fi - from Figure 3 for the desired retort temperature.

log jI - from the heat penetration curve or by taking the logarithm of the product of j and (RT-IT). (see Figure 2).

log g (equation 2) - from Figure 3 for the corresponding value of f_h/U determined by dividing f_h by the product of F_o and Fi. That is, F_o x Fi = U.

f_2 - from the heat penetration curve (see Figure 2).

f_h/U_{h2} - from Figure 3 for the corresponding value of log g_{h2} which may be calculated by the equation:

$$\log g_{h2} = \frac{f_h \log jI + (f_2 - f_h) \log g_{bh} - B_B}{f_2}$$

log g_{bh} - from the heat penetration curve, where g_{bh} = retort temperature minus the temperature at which the curve suffers a change in slope. If x_{bh} is given as a condition of the problem rather than g_{bh}, the latter may be calculated by solving this equation:

$$\log g_{bh} = \log jI - \frac{x_{bh}}{f_h}$$

r_{bh} - from Figure 4 for the corresponding value of log g_{bh}.

f_h/U_{bh} - from Figure 3 for the corresponding value of log g_{bh} which may be calculated by the equation: $\log g_{bh} = \log jI - \frac{x_{bh}}{f_h}$, x_{bh} being the time from the beginning of the process to the break in the heat penetration curve. (see Fig. 2)

log g_{h2} - from Figure 3 for the corresponding value of f_h/U_{h2}. This value of f_h/U_{h2} may be calculated by rearrangement of equation 3 thusly:

$$f_h/U_{h2} = \frac{f_2}{F_o Fi + \frac{r_{bh}\,(f_2 - f_h)}{f_h/U_{bh}}}$$

If F_o is not known, then B_B must be known and this following equation is used to find log g_{h2}:

$$\log g_{h2} = \frac{f_h \log jI + (f_2 - f_h) \log g_{bh} - B_B}{f_2}$$

We now have accounted for all of the terms in the equations and are in a position to solve any problem for which are provided the proper specifications. Let us go through a few samples in order to become a little more familiar with the procedure. We will take the simplest problem first where the heating curve exhibits no change in slope. The following data are given:

Example #1

f_h = 12.9

j = 1.51

IT = 160°F.

RT = 250°F.

F_o = 2.78 (Desired Sterilizing Value)

B_B = ?

The equation for B_B which involves a simple heating curve without a change in slope is #2: $B_B = f_h (\log jI - \log g)$. The unknown terms are f_h, log jI and log g. The given data tells us the value of f_h and also the necessary information for figuring easily the value for log jI.

I = RT - IT = 250 - 160 = 90

Then jI = 1.51 x 90 = 135.9

and log jI = 2.13 (from Figure 4)

Log g is determined from Figure 3 but we must first know f_h/U. By definition $U = F_o \times Fi$, and Fi = 1.0 from figure 3 for RT = 250. So U = 2.78 x 1 = 2.78 and f_h/U = 12.9/2.78 = 4.64.

Referring now to Figure 3 we can obtain a value of log g for f_h/U = 4.64 and we find that log g = .7

Equation 2 can now be written thusly and the solution obtained:

B_B = 12.9 (2.13 - .7) = 12.9 x 1.43 = 18.5 minutes

Example #2

Now, we will change our conditions somewhat so that:

f_h = 12.9

j = 1.51

IT = 160°F.

RT = 235°F.

B_B = 45 minutes

F_o = ? (Desired sterilizing value)

For this problem we will use equation 1 because F_o is the unknown. The terms which we must substitute are f_h, f_h/U, and Fi. The first of these, f_h, is given in the specifications (f_h = 12.9). The second, f_h/U, must be obtained from Figure 3 for a value of log g which we do not yet know but which can be calculated, as previously stated, by this equation:

$$\log g = \log jI - \frac{B_B}{f_h}$$

All of the terms on the right hand side of this equation are either given or can be easily determined from the specifications.

I = RT - IT = 235-160 = 75

jI = 1.51 x 75 = 113.2

In the absence of log tables or slide rule, log jI can be ascertained by reference to figure 4.

log jI = 2.05

B_B/ f_h = 45/12.9 = 3.49

log g = log jI - B_B/f_h = 2.05 - 3.49 = -1.44

Referring now to figure 3 we find a value of f_h/U = .465 for log g = -1.44

The retort temperature is 235°F. so from Figure 3 we find the value of Fi corresponding to RT = 235°F. to be 6.8.

Substituting in Equation 1

$$F_o = \frac{f_h}{(f_h/U)\ Fi} = \frac{12.9}{.465 \times 6.8} = 4.1$$

Example #3

Now let's further change our conditions to get into another type of problem:

$f_h = 12.9$

$f_2 = 70$

$j = 1.51$

$x_{bh} = 14.8$

$IT = 167°F$

$RT = 240°F$

$B_B = 50$ minutes (Known process time)

$F_o = ?$ (Unknown sterilizing value)

What equation do we use? Well, it must be #3 because the curve exhibits a change in slope and the sought quantity is F_o. This may be rewritten with substitution of the values given by the specified conditions:

$$F_o = \frac{70}{(f_h/U_{h2})\ Fi} \quad — \quad \frac{r_{bh}\ (70 - 12.9)}{Fi\ (f_h/U_{bh})}$$

The values of f_h/U must be found from their corresponding values of log g from figure 3 and the values of log g must be calculated by the following equations:

$$\log g_{bh} = \log jI - \frac{x_{bh}}{f_h}$$

$$= \log 1.51\ (240\text{-}167°F.) - \frac{14.8}{12.9}$$

$$= \log 110 - 1.15$$

$$= 2.04 - 1.15 = .89$$

(In the absence of log tables, log jI = 2.04 can be ascertained by reference to figure 4)

$$\log g_{h2} = \frac{f_h \log jI + (f_2 - f_h) \log g_{bh} - B_B}{f_2}$$

$$= \frac{12.9 \log 110 + (70 - 12.9)\ 0.89 - 50}{70}$$

$$= \frac{26.3 + 50.8 - 50}{70}$$

$$= .387$$

By reference to figure 3 we find for these calculated values of log g_{bh} and log g_{h2}:

$f_h/U_{bh} = 8.1$

$f_h/U_{h2} = 2.3$

Fi can also be found from Figure 3 for a retort temperature of 240°F.

Fi = 3.6

The term r_{bh} is found from Figure 4 for the corresponding value of log g_{bh}.

$r_{bh} = .76$ (from log $g_{bh} = .89$ on Fig. 4.)

Now the equation can be solved.

$$F_o = \frac{70}{2.3 \times 3.6} - \frac{.76\ (70-12.9)}{3.6 \times 8.1}$$

$$= 8.4 - 1.5 = 6.9$$

Example #4

A problem involving equation 4 is a bit tricky but is solved by this systematic procedure. We will take the same conditions just given except that we will solve for B_B using an F_o value of 6.9. Therefore, we know B_B should check the 50 minute value given in the previous example.

Given $f_h = 12.9$

$f_2 = 70$

$j = 1.51$

$x_{bh} = 14.8$

IT = 167

RT = 240

$F_o = 6.9$

B_B = ? (unknown process time)

Equation 4, $B_B = f_h \log jI + (f_2 - f_h) \log g_{bh} - f_2 \log g_{h2}$

The terms log jI and log g_{bh} are calculated as in the previous example. The term log g_{h2} must be determined from the corresponding value of f_h/U_{h2} which must be calculated by solution of this equation:

$$f_h/U_{h2} = \frac{f_2}{F_o\ Fi + r_{bh}\ \frac{(f_2 - f_h)}{f_h/U_{bh}}}$$

The terms Fi, r_{bh} and f_h/U_{bh} must be determined as in the previous example by reference to Figures 3 and 4. As before, log g_{bh} is calculated to be 0.89 and log jI to be 2.04.

Fi (See Fig 3, RT = 240°F.) = 3.6

r_{bh} (See Fig. 4, log g_{bh} = .89) = .76

f_h/U_{bh} (See Fig. 3, log g_{bh} = .89) = 8.1

Then $f_h/U_{h2} = \frac{70}{6.9 \times 3.6 + \frac{.76\ (70-12.9)}{8.1}}$

Then $f_h/U_{h2} = \frac{70}{24.8 + 5.36} = 2.32$

Referring again to Figure 3 a value of log g_{h2} = .38 is found for f_h/U_{h2} = 2.32.

We can now complete the substitutions in equation 4.

B_B = 12.9 x 2.04 + (70-12.9) x .89 - 70 x .38

= 26.3 + 50.8 - 26.6

= 50.5, which, to two significant figures, is 50 minutes.

Suppose the problem does not involve sterilizing value or F_o but merely requires the calculation of time required to reach a certain can center temperature (CT) or the calculation of the temperature in the center of the can after a certain heating time. This involves the solution of equation 2 or 4 with substitution of RT-CT for the term g or g_{h2}. Either CT or B_B can be computed without a great deal of difficulty.

It should perhaps be stated here that the methods used above do not involve corrections for a number of factors which do not greatly affect the final results. The original Ball method includes these corrections, but they have been eliminated in the interests of brevity as they are not important from practical considerations. For further study of this method the technologist is referred to the literature as given in the bibliography.

Also the original method estimated the parameters to four or more significant figures but these have been reduced to two or at the most, three, because it almost never will be found necessary to estimate a process time or F_o value to more than two significant figures.

Effect of Cooling Curve

In the formulae previously discussed no mention was made of the rate of change of the can temperature during the cooling phase of the process. Of course, the can temperature may remain above 214°F. during the cooling cycle for an appreciable period, during which time a significant quantity of lethal heat is being brought to bear against any surviving micro-organisms. It may seem strange that this has apparently been given no consideration.

As a matter of fact the lethality during the cooling cycle has been taken into account in these formulae by assuming that the slope of the cooling curve bears a constant relationship to the heating curve factors. The cooling curve slope, identified by the symbol f_c, has been assumed equivalent to the heating curve slope, f_h, or, in the case of a broken heating curve, equivalent to the heating curve slope f_2 of the second part of the curve. This assumption introduces no significant error for the simple heating curve type of problem but this may not be true for the broken heating curve type of problem. A product which initially heats by fast convection and then changes to slower convection may, quite likely, initially cool by fast convection. The cooling slope f_c, therefore, can be approximated more accurately by f_h than by f_2.

An empirical method for making this cooling curve correction for broken heating curve problems has been worked out which is applicable over any practical range of f_c values. Briefly stated, it depends on a correction to the log g_{h2} value depending on the value of the ratio f_c/f_2. For constant values of f_h/U, the value of log g_{h2} is decreased by 0.007 for each .1 deviation from unity of the ratio $\frac{f_c}{f_2}$. The value of log g_{h2} may thus be corrected by adding or subtracting the term $.07(1-\frac{f_c}{f_2})$. When calculating B_{13} it is subtracted. When calculating F_o it is added.

Example #3 may be recalculated by assuming that $f_c = f_h$ instead of f_2 so that $\frac{f_c}{f_2} = .185$. The problem is identically solved until we come to the step where $\frac{f_h}{U_{h2}}$ is derived from Figure 3. Log g_{h2} was found to be .387 which we must adjust by adding: $.07(1-\frac{f_c}{f_2})$

$$\text{Log } g_{h2} \text{ (corrected)} = .387 + .07(1 - .185)$$

$$= .387 + .057$$

$$\text{Log } g_{h2} \text{ (corrected)} = .444$$

Now by reference to Figure 3 we find the new value of $\frac{f_h}{U_{h2}}$ to be 2.6.

This new value is substituted in equation #3 and the new solution obtained as follows

$$F_o = \frac{70}{(f_h/U_{h2})\ F_i} - \frac{r_{bh}\ (70-12.9)}{F_i\ \ (fh/Ubh)}$$

$$= \frac{70}{2.6 \times 3.6} - \frac{.76\ (70-12.9)}{3.6 \times 8.1}$$

$= 7.5 - 1.5 = 6.0$, which compares with the value of 6.9 calculated for the condition $f_c = f_2$.

Similarly we can recalculate the problem of example 4. Referring back to this problem it will be noted that a value of log g_{h2} of .380 was found. This value is corrected by subtracting .057 and finding the corrected value to be:

$$\log g_{h2} \text{ (corrected)} = .380 - .057 = .323$$

The solution is then completed by substituting in equation 4 as follows:

$$B_B = f_h \times \log jI + (f_2 - f_h) \log g_{bh} - f_2 \log g_{h2}$$

$$= 12.9 \times 2.04 + (70-12.9) \times .89 - 70 \times .323$$

$$= 26.3 + 50.8 - 22.6$$

$= 54.5$ which compares with the value of 50.5 minutes calculated for the condition of $f_c = f_2$. This 4 minute difference may be of considerable importance.

Can Size Conversion

Although it is recommended that heat penetration data be obtained on the particular size can for which a process is desired, such information is not always at hand. Sometimes a

process may be desired on a product in a can size in which it has never been packed and, for one reason or another, it is not physically possible to obtain the necessary data. In such instances the only feasible procedure is to estimate the new heat penetration factors thru theoretical considerations. We will not attempt to wade through the fundamental calculations involved in deriving these equations but will simply offer them without proof and demonstrate their usefulness. For those mathematically inclined individuals interested in the derivations, references to the original work are quoted in the appended bibliography.

Heat transfer occurs in canned foods by conduction or convection or by a combination of the two. A conduction heating product will invariably yield a simple type heating curve, that is, it can be represented as a straight line on semilog graph paper and the f_h value in a #2 size can will be in the range 50 to 70 minutes. A convection heating product may also produce a simple curve, as for example, peas and evaporated milk. The f_h value for these products, however, will almost always be less than 10. More often, the convection heating products yield heating curves which exhibit a change in slope probably resulting from a reduction in the force of the convection currents as the temperature difference decreases.

Conduction Heating

The f_h value for conduction heating products in cylindrical cans has been shown to be simply a function of the dimensions of the can and of a factor fixed by the product called the diffusivity constant. The f_h value then is proportional to the can dimensions according to the following equation: $f_h = \frac{d^2 f_{II}}{k}$ where $d^2 f_{II}$ is the can factor dependent on the can dimensions and k is the diffusivity constant. By substituting known values of f_h and $d^2 f_{II}$, k can be calculated and substituted in an identical equation with a different value of $d^2 f_{II}$ for the solution of f_h.

The values of $d^2 f_{II}$ are given in the appended Figure 7 for all practical can dimensions. To show how this computation is carried out an example problem has been set up:

Example: Suppose a #2 can (307 x 409) of a product has a heating slope (f_h) of 60 and a j value of 1.8. It is desired to compute the f_h value for the same product in a #1 can (211 x 400). Referring to Figure 7 the $d^2 f_{II}$ values for the #1 and #2 cans

are found respectively to be 2.2 and 3.5. The f_h values are proportional to these figures so

$$\frac{f_{h1}}{f_{h2}} = \frac{(d^2 f_{II})1}{(d^2 f_{II})2}$$

$$\frac{f_{h1}}{60} = \frac{2.2}{3.5}$$

$$fh1 = \frac{60 \times 2.2}{3.5} = 37.7$$

The j value is usually assumed invariable with a can size change.

It will be noted that Figure 7 is arranged to make the proportional computation of f_h for the different can sizes. The horizontal lines representing the different can sizes, which can be picked off the curves on the left side of the figure, can be extended to intersect the vertical line on the right side of the figure representing the known f_h value. A straight line falling on this intersection and the origin of the graph will, for a given product, intersect all other horizontal lines representing different can sizes, at their vertical f_h lines.

Some food containers have a general rectangular shape and the equation for the cylindrical can does not apply.

For the rectangular can the following equation applies:

$$f_h = \frac{.233\ w^2\ t^2\ l^2}{k(w^2\ t^2 + w^2\ l^2\ t^2)}$$

Where w, t, and l are the can dimensions. A seam correction of 1/4" should be subtracted from the nominal length, and 1/8" from the nominal width and thickness to apply in this equation.

The procedure involved is the same as for the cylindrical can. If the diffusivity constant is computed from the cylindrical can equation it can be substituted directly in the rectangular can equations, the dimensions substituted and the equation solved for f_h.

Convection Heating

Different equations must be used for convection heating products because of the different mode of heat transfer involved. A homogeneous fluid product heating by convection will have a heating slope proportional to the can dimensions in the following relationship:

$f_h = \frac{av}{S}$ where v and S are the volume and surface area of the can respectively and a is a constant of proportionality. The volume and surface area can be stated in terms of radius and height and the proportional equation then becomes:

$$\frac{f_{h1}}{f_{h2}} = \frac{r_1 \ h_1}{r_1 + h_1} \times \frac{r_2 + h_2}{r_2 \ h_2}$$

To use this equation in a practical problem 1/16" should be subtracted from the radius and 1/4" from the height to correct for the seam dimensions.

Example: A #2 can of evaporated milk has an f_h value of 5. What is the f_h value for a #1 can of the same product?

$$r_1 = \frac{2\ 11/16}{2} - \frac{1}{16} = \frac{41}{32} = 1.28$$

$$h_1 = 4 - \frac{1}{4} = 3.75$$

$$r_2 = \frac{3\ 7/16}{2} - \frac{1}{16} = \frac{53}{32} = 1.66$$

$$h_2 = 4\frac{9}{16} - \frac{1}{4} = \frac{69}{16} = 4.32$$

$$\frac{f_{h1}}{5} = \frac{1.28 \times 3.75}{1.28 + 3.75} \times \frac{1.66 + 4.32}{1.66 \times 4.32} = \frac{4.8}{5.03} \times \frac{5.98}{7.17}$$

$$f_{h1} = \frac{5 \times 4.8 \times 5.98}{5.03 \times 7.17} = 4.$$

Tabulation of convection can factors for various can sizes will considerably expedite the solution of this problem. Such a tabulation is appended as Table I for most of the common can sizes.

The Nomogram Method, or the Method of Olson & Stevens, and Roberts

The nomogram method is merely a graphical solution of the equations given in the previous section. No additional reference to charts, log tables, or slide rules is needed; only a straight edge (preferably transparent) is required.

Different nomograms are required for the two types of problems represented by a single straight line heating curve and a broken or two-slope heating curve. Nomogram figure 5 is used for the straight line heating curve problem and figure 6 for the broken heating curve problem. The use of figure 5 will be described first.

Nomograms for Simple Straight Line Heating Curve

Let us take the example #1 given previously and solved by formula where the following data are given:

Example #5

RT = 250°F.

IT = 160°F.

j = 1.51

f_h = 12.9

F_o = 2.78

B_B = Value to be obtained.

With these values and Figure 5, B_B is determined by the following steps:

Step 1: On Figure 5, connect F_o (2.78) on scale 1 to RT (250°F.) on scale 4; get a point on scale 3.

Step 2: Connect point on scale 3 to f_h (12.9) on scale 2; get a new point on scale 4.

Step 3: Follow parallel to the ladder lines between scales 4 and 5 from new point on scale 4 to point on scale 5. Mark this point.

Step 4: Connect j (1.51) on scale 5 to RT-IT (250-160 = 90) on scale 7, get a point on scale 6.

Step 5: Connect point on scale 6 to marked point on scale 5 and get new point on scale

Step 6: Connect this new point on scale 7 with f_h (12.9) on scale 8 and get B_B = 18.5 on scale 9.

Note: There are two scales 8, one marked 8A and the other 8 B. The one to use depends on which of the ladder arrangements between scales 4 and 5 was used. The A lines start

on the lower two-thirds of scale 4 and the B lines start on the upper third. Which ladder to use depends on the condition of the problem and whichever one is used, the corresponding scale 8 must be also used.

If you have followed through with this example you will recognize the answer, 18.5 minutes as identical with the figure obtained by the formula method.

Example #6

Let's try the other example which was solved by the formula as example #2. The conditions are:

f_h = 12.9

j = 1.51

IT = 160°F.

RT = 235°F.

B_B = 45 minutes

F_o = value to be obtained

For the solution of this problem follow this procedure:

Step 1: On figure 5 connect B_B (45) on scale 9 with f_h (12.9) on scale 8 and get a point on scale 7. Immediately a decision is necessary as to which scale 8 to use, 8A or 8B. Trial and error is the only satisfactory means of selecting the proper scale. Suppose, as a first trial, we use 8A. Mark the point on scale 7.

Step 2: Connect RT-IT (235-160 = 75) on scale 7 with j (1.51) on scale 5 and get a point on scale 6.

Step 3: Connect this point with marked point on scale 7 and get a point on scale 5. With the figures chosen we are off scale 5 which means that we have selected the wrong scale 8. It is then necessary to repeat from step 1.

Repeat Step 1. Connect B_B (45) on scale 9 with f_h (12.9) on scale 8B and get a point on 7. Again we are in "off scale" trouble but this time draw an extension to scale 7 to get the point up near the edge of the paper.

Repeat Step 2: As before.

Repeat Step 3: As before. The point is found to be ok about 360 on scale 5.

Step 4: From this point on scale 5 follow the ladder lines to scale 4 and get a point.

Step 5: Connect this point with f_h (12.9) on scale 2 and get a point on scale 3.

Step 6: Connect this point with RT (235) on scale 4 and read F_o on scale 1. F_o should be found to be within a few tenths of the figure determined by formula, in this example, 4.1. This error is usually not significant but is minimized when a sharp pencil and special care is used in marking the points.

The example just chosen was an unusual one in that more "off scale" trouble was encountered than will be found most of the time. Once in a great while a problem will arise which is beyond the scope of the nomogram in which case the best course is the formula method.

There are a few simple tricks that can be used to make some problems workable on the nomogram which at first glance might appear to be out of range. B_B on scale 9 of figure 5 only includes the range 0 to 120 minutes, and process times longer than this are not uncommon. A little study will show that a line passing through a given point on scale 7 intersects scale 8 and 9 so that the ratio of B_B to f_h is constant. Therefore, the same ratio can be maintained when both B_B and f_h are multiplied or divided by the same number. If B_B is 180 minutes, a line should be drawn between $180/2 = 90$ and $f_h/2$ which will give the identical point on scale 7 that would have been found if the line had been drawn between the real values of B_B and f_h.

A line drawn through a point on line 3 at any angle will intersect points on scales 1 and 4 so that for every increase in the value of RT by 18 the value of F_o is increased 10 fold. This means that if the retort temperature is 270°F. the value on the scale can be taken as 252°F. providing the value of F_o is divided by 10.

Nomogram for Broken Heating Curve

A different nomogram is necessary when the heat penetration curve undergoes a change in slope. This is shown as Figure 6. In solving a problem involving this condition we simply follow the steps as outlined below using nomogram figure 6. For convenience we will use the same sample problem that was used in describing the formula method. The factors as given are:

Example #7

$f_h = 12.9$

$f_2 = 70$

$j = 1.51$

$x_{bh} = 14.8$

IT = 167°F.

RT = 240

B_B = 50 minutes (known process time)

F_o = ? (unknown sterilizing value to be determined)

Step 1: Connect x_{bh} (14.8) on scale 1 to f_h (12.9) on scale 4, get point on scale 5 and mark.

Step 2: Connect j(1.51) on scale 7 to RT- IT (240-167 = 73) on scale 5, get point on scale 6.

Step 3: Connect point on scale 6 to marked point on scale 5 and get g_{bh} (= 7.8) on scale 7.

Step 4: Follow ladder from g_{bh} (7.8) to point on scale 8.

Step 5: Connect this point on scale 8 to f_2 - f_h (70-12.9 = 57.1) on scale 11, get U_3 (= 5) on scale 9, and mark.

Step 6: Connect B_B - x_{bh} (50-14.8 = 35.2) on scale 2 to f_2 (70) on scale 3 and get point on scale 5.

Step 7: Connect this new point to g_{bh} (7.8, from Step 3) on scale 7 and get new point on scale 6.

Step 8: From this new point on scale 6, follow the ladder to new point on scale 7.

Step 9: Connect this point on scale 7 to f_2 (70) on scale 10 and get U_4 (= 29) on scale 6.

Step 10: Subtract mentally U_3 (= 5. from step 3) from U_4 (= 29 from Step 9) to get U_o (= 24).

Step 11: Connect U_o(24) on scale 6 to 250 on scale 8 and get point on scale 7.

Step 12: Connect this point on scale 7 to RT (240°F.) on scale 8, get F_o (= 6.7) on scale 6.

This answer, F_o = 6.7, is 0.2 less than we obtained using the formula method but for most purposes this error is insignificant. Obviously, the nomogram is most accurate when sharp pencils and care are used in placing the various points.

Example #8

By reversing the order of these steps and with F_o given instead of B_B we can solve a broken heating curve problem finding the process time, B_B. Here is a set of assumed conditions which will serve as an example for this type of problem:

F_o = 10

f_h = 10

f_2 = 35

x_{bh} = 8

j = 1.2

RT = 235°F.

IT = 160°F.

The problem is solved using figure 6 as follows:

Step 1: Connect x_{bh} (8) on scale 1 to f_h (10) on scale 4, get point on scale 5 and mark.

Step 2: Connect j (1.2) on scale 7 to RT-IT (235-160 = 75) on scale 5, get point on scale 6.

Step 3: Connect point on scale 6 to marked point on scale 5 and get g_{bh} (= 14) on scale 7.

Step 4: Follow ladder from g_{bh} (14) to point on scale 8.

Step 5: Connect this point on scale 8 to f_2 - f_h (35-10 = 25) on scale 11, get U_3 (=.7) on scale 9 and mark.

Step 6: Connect F_o (10) on scale 6 with RT (235) on scale 8, get point on scale 7.

Step 7: Connect this point on scale 7 with RT (250) on scale 8, get U_o (= 68) on scale 6.

Step 8: Add mentally U_o (68, from step 7) to U_3 (.7 from step 5), get U_4 (= 68.7)

Step 9: Connect U_4 (68.7) on scale 6 with f_2 (35) on scale 10, get new point on scale 7.

Step 10: Follow the ladder from this point and get a point on scale 6.

Step 11: Connect this point on scale 6 with g_{bh} (14) from step 3 on scale 7 and get a point on scale 5.

Step 12: Connect this point on scale 5 with f_2 (35) on scale 3 and get B_B-x_{bh} (= 85.5) on scale 2.

Step 13: Add mentally B_B - x_{bh} (85.5) from step 12 to x_{bh} (8) and get B_B = 93.5 minutes.

The formula solution of this problem gives 91 minutes but, again, this difference is of no practical significance because the actual process would most likely be rounded off to 90 or 95 minutes in either case.

A problem unsolvable by these nomograms because of "off scale" difficulty will always be solvable by formula. Probably only 5% or less of processing problems will will be out of range of the nomograms.

SUFFIX

It should be noted that there are grounds for criticism of the instructions on the basis of the strictest mathematical accuracy of the calculations. In the interests of simplicity no allowance has been made for variations in m + g, nor has the z value ever been mentioned. These values have been assumed as 180°F. and 18°F., respectively, which are average values of these parameters.

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APPENDIX

Definition of Terms and Symbols

Term	Symbol	Definition
Sterilizing Value	F_o	The equivalent value of the process in terms of minutes at 250°F. when no time is involved in heating to 250°F. or cooling to sublethal temperatures. (The equivalent time at other temperatures must also be fixed but for the purpose of this discussion this is not necessary and will be ignored.)
Process Time	B_B	The time in minutes from the beginning of the process to the end of the heating period.
Retort Temperature	RT	The temperature in °F. of the medium in which the containers are processed.
Can Temperature	CT	The temperature of the can content at the slowest heating point.
Cooling Water Temperature	CW	The temperature of the cooling water in °F.
Initial Temperature	IT	The value of CT at the beginning of the process.
	I	A factor representing the difference between the retort temperature and the initial temperature, ie., I = RT-IT
Heat Penetration Curve or Heating Curve	-	The line described by the temperature of the slowest heating point in a can when plotted against time.
Heat Penetration Curve Slope, or Heating Curve Slope	f_h	The number of minutes required for the straight line portion of the heating curve plotted on semi-logarithmic paper to pass through the points (RT-n) and (RT-10n) where n can have any convenient value.
Second Slope of Heating Curve	f_2	When the heating curve is expressed as a broken curve (two straight lines of different slope) this term represents the number of minutes required for the second portion of the curve to pass through the points (RT-n) and (RT-10n) where n can have any convenient value.
Cooling Curve Slope	f_c	The number of minutes required for the cooling curve, when plotted on semi-logarithmic paper, to pass through the points (CW + n) and (CW + 10n) where n can have any convenient value.

Term	Symbol	Definition
Lag Factor	j	A number representing the time lag before RT-CT assumes straight line characteristics on semi-log paper with time. Mathematically this time lag in minutes is equal to f_h x log j.
	g_{bh}	The number of degrees below retort temperature at which the heating curve exhibits a change of slope
	g or g_{h2}	The number of degrees below retort temperature on the heating curve at the end of the heating period.
	r_{bh} f_h/U_{h2} f_h/U_{bh}	Factors related to g values having corresponding subscripts in accordance with Figures 3 & 4.
	U or U_o	Sterilizing value in terms of minutes at retort temperature.
	U_3	Difference in sterilizing value between that which obtains when heat penetration curve has slope of f_h and when it has slope of f_2 for a g value equal to g_{bh} without considering the lethal value under the cooling portion of the curve.
	U_4	Sterilizing value if heat penetration curve has single slope equal to f_2.
	Fi	Factor which is multiplied by F_o to give U: Fi x F_o = U. Mathematically log Fi = $\frac{250 - RT}{18}$
	x_{bh}	Number of minutes from the beginning of the process to the point of break in the heating curve.

Synopsis of Useful Equations

For simple heating curves -

1. $F_o = \dfrac{f_h}{(f_h/U)Fi}$

1a. $\log g = \log j\ I - \dfrac{B_B}{f_h}$

2. $B_B = f_h\ (\log j\ I - \log g)$

2a. $\dfrac{f_h}{U} = \dfrac{f_h}{F_o \times Fi}$

For broken curve problems -

3. $F_o = \dfrac{f_2}{(f_h/U_{h2})\ Fi} - \dfrac{r_{bh}\ (f_2 - f_h)}{Fi\ (f_h/U_{bh})}$ (When $f_c = f_2$)

3a. $\log g_{bh} = \log j\ I - \dfrac{x_{bh}}{f_h}$

3b. $\log g_{h2} = \dfrac{f_h \log jI + (f_2 - f_h) \log g_{bh} - B_B}{f_2}$

4. $B_B = f_h \log jI + (f_2 - f_h) \log g_{bh} - f_2 \log g_{h2}$ (when $f_c = f_2$)

4a. $\dfrac{f_h}{U_{h2}} = \dfrac{f_2}{F_o\ Fi + \dfrac{r_{bh}\ (f_2 - f_h)}{f_h/U_{bh}}}$

5 $\log g_{h2}$ correction $= .07\ (1-\dfrac{f_c}{f_2})$ (Empirical correction when f_c has any value). To be added to $\log g_{h2}$ when calculating for F_o and to be subtracted from $\log g_{h2}$ when calculating for B_B.

6. $F_o = \dfrac{f_2\ r_{h2} + f_c(1-r_{h2})}{Fi(f_h/U_{h2})} - \dfrac{r_{bh}\ (f_2 - f_h)}{Fi\ (f_h/U_{bh})}$

(Rigorous solution when f_c has any value)

7. $$\frac{f_h}{U_{h2x}} = \frac{(f_h/U_{h2})\ f_2}{r_{h2}\ (f_2 - f_c) + f_c}$$

(In this instance f_h/U_{h2x} is the value of f_h/U_{h2} corrected for a cooling curve slope value (f_c) different from f_2.

8. $$f_h/U_{h2} = \frac{1}{(.62 - \log g_{h2})\ (1 - \frac{f_c}{f_2}) + \frac{f_c}{f_2}\ (.71 - \log g_{h2})}$$

(When $\log g_{h2}$ is less than -1.)

9. $$r_{h2} = \frac{.62 - \log g_{h2}}{.71 - \log g_{h2}}$$

(When $\log g_{h2}$ is less than -1.)

Miscellaneous

10. $$\log Fi = \frac{250 - RT}{18}$$

11. $$Fi \times F_o = U_o$$

Table I

Can Factors for Convection Heating

Can Size	Factor	Can Size	Factor
202 x 204	.666	307 x 113	.804
202 x 214	.724	307 x 203	.893
202 x 308	.765	307 x 208	.954
202 x 314	.784	307 x 214	1.015
211 x 200	.740	307 x 306	1.082
211 x 210	.832	307 x 400	1.149
211 x 212	.847	307 x 409	1.197
211 x 300	.874	307 x 510	1.266
211 x 304	.898	307 x 512	1.273
211 x 400	.955	307 x 704	1.339
211 x 414	1.003	401 x 207.5	1.043
211 x 600	1.048	401 x 411	1.363
300 x 106	.631	404 x 307	1.252
300 x 200	.789	404 x 404	1.361
300 x 206	.857	404 x 414	1.426
300 x 308	.996	404 x 700	1.579
300 x 400	1.039	502 x 510	1.707
300 x 407	1.070	603 x 408	1.769
301 x 411	1.103	603 x 600	1.985
303 x 406	1.117	603 x 700	2.092
303 x 509	1.188	603 x 812	2.234

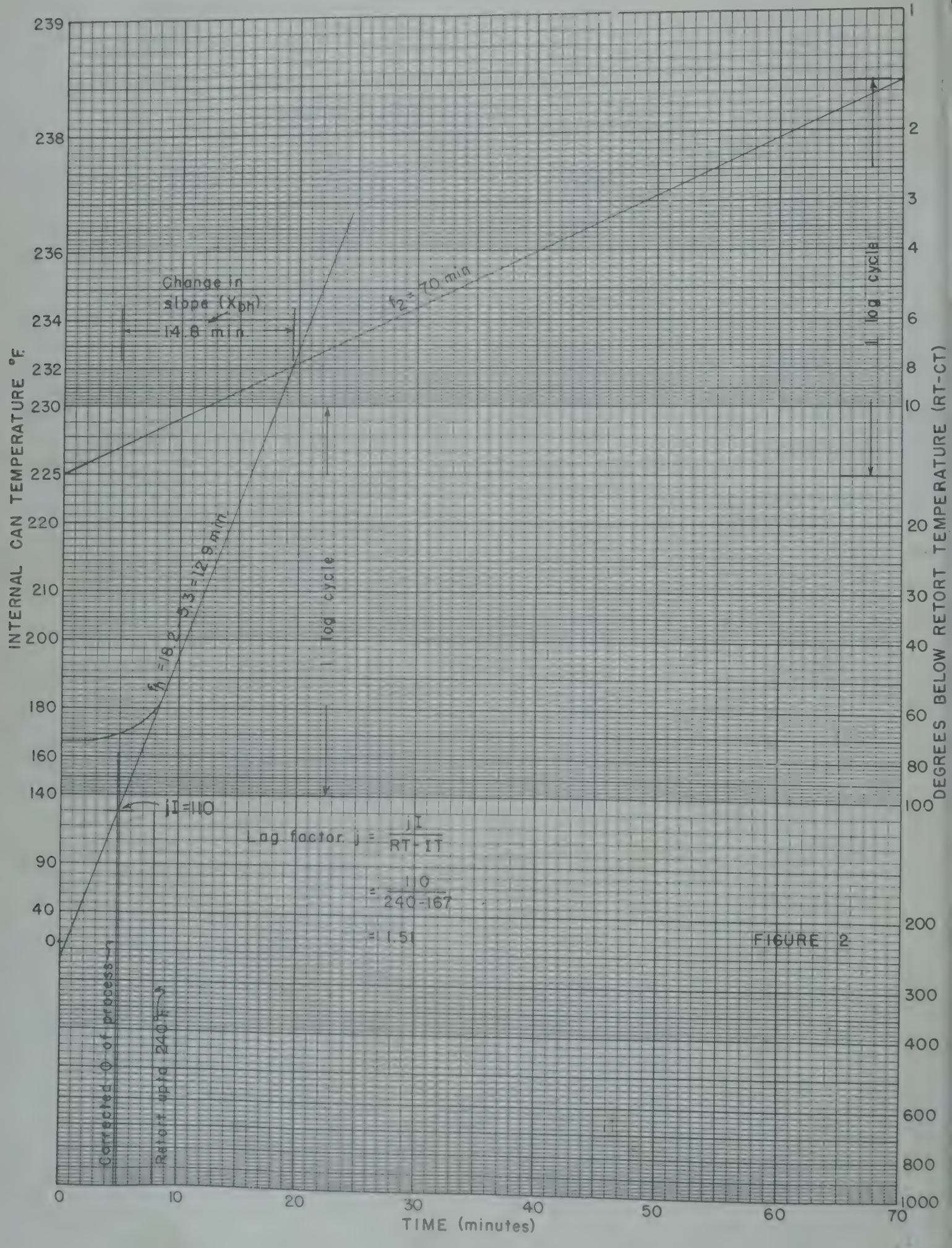

INTERNAL CAN TEMPERATURE °F
DEGREES BELOW RETORT TEMPERATURE (RT-CT)
TIME (minutes)
239
238
236
234
232
230
225
220
210
200
180
160
140
90
40
0
1
2
3
4
6
8
10
20
30
40
60
80
100
200
300
400
600
800
1000
0
10
20
30
40
50
60
70
Change in slope (Xpn)
14.8 min.
f2 = 10 min
fh = 18.2
f1 = 12.8 min
1 log cycle
1 log cycle
jI = 110
Lag factor, j = jI / (RT - IT)
= 110 / (240 - 167)
= 1.51
Corrected 0 of process
Retort up to 240°F

FIGURE 2

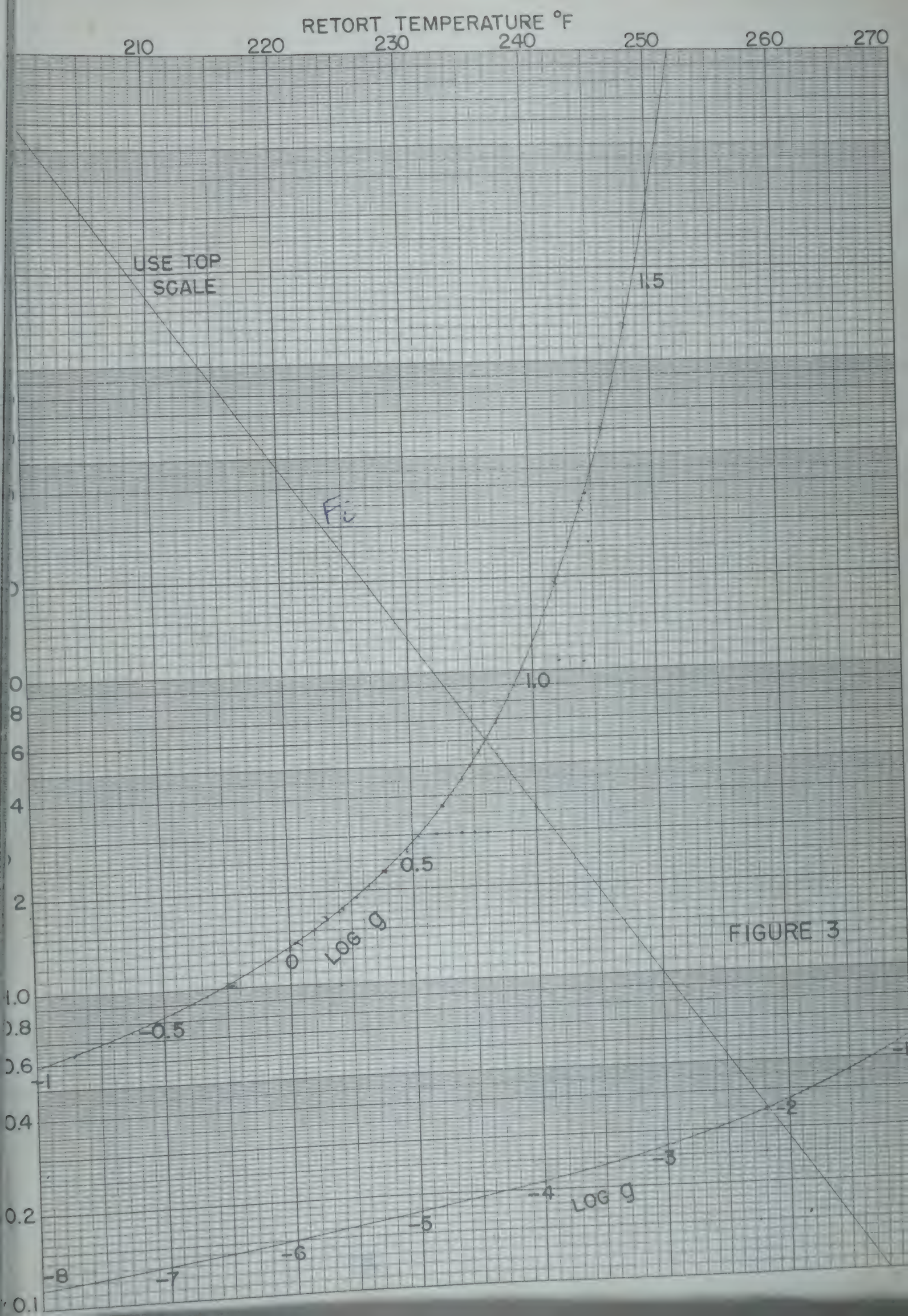

RETORT TEMPERATURE °F
210
220
230
240
250
260
270
USE TOP SCALE
Fi
1.5
1.0
0.5
0
-0.5
-1
-2
-3
-4
-5
-6
-7
-8
LOG g
0.8
0.6
0.4
0.2
0.1

FIGURE 3

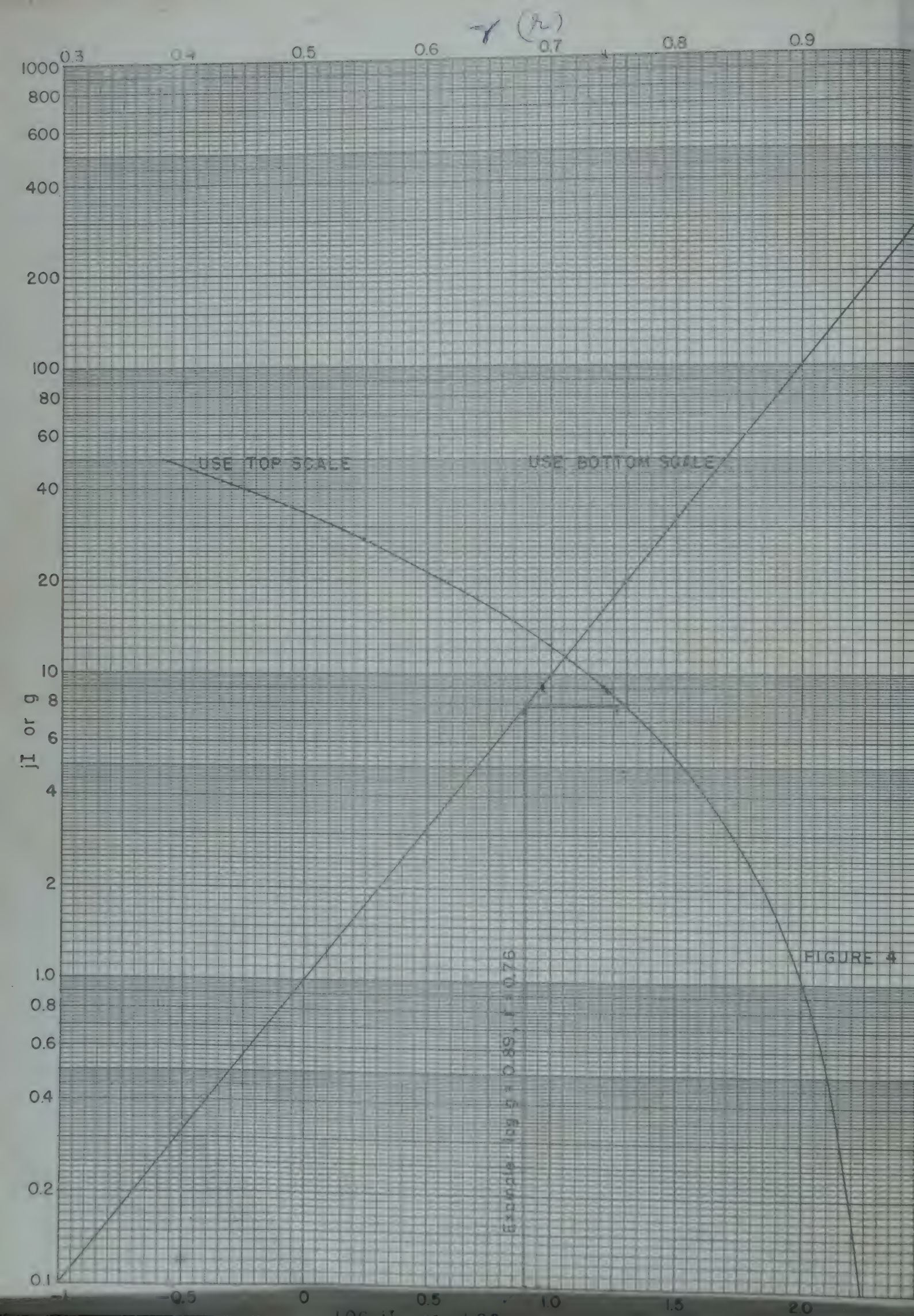
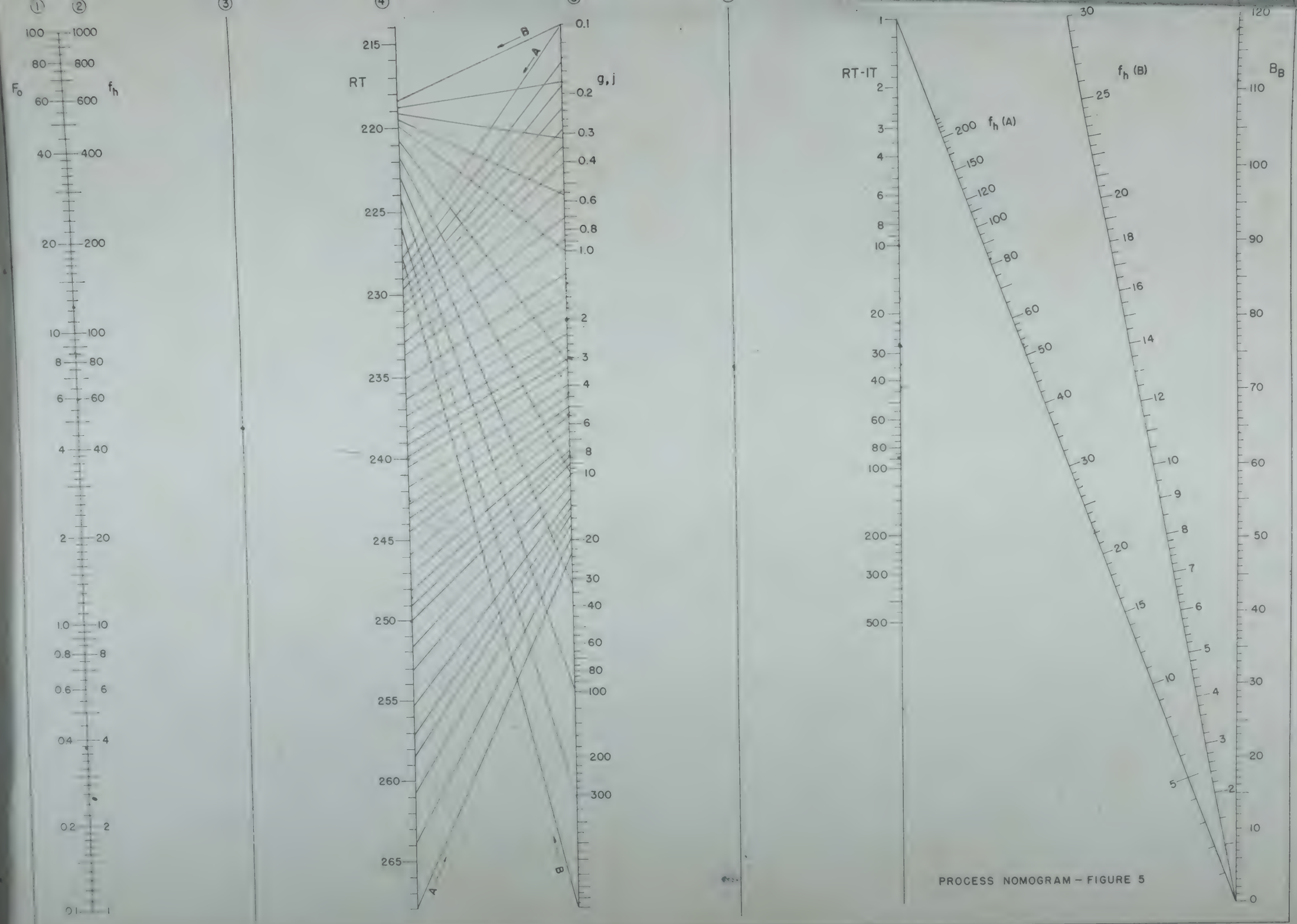
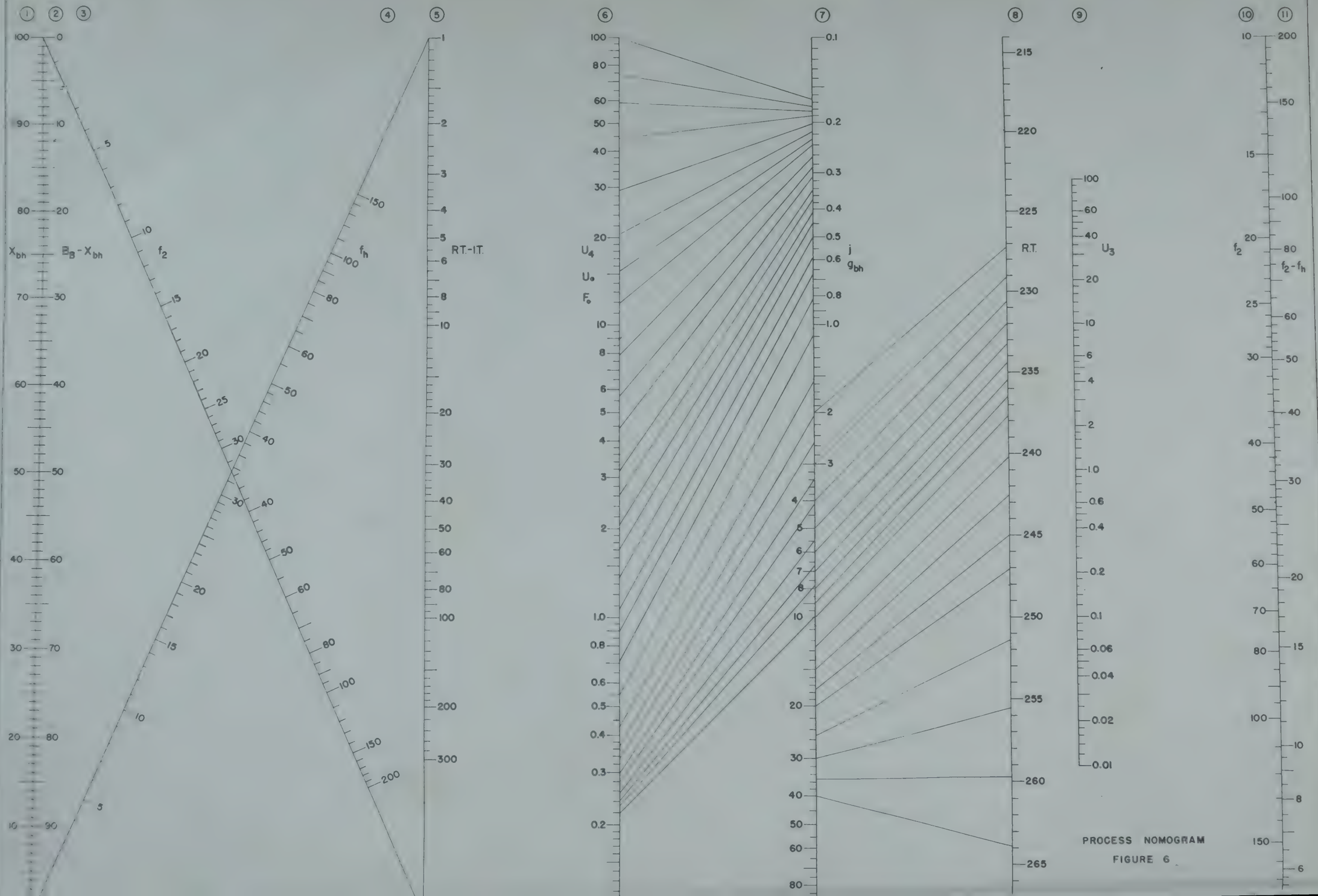

-γ (R)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1.0
0.8
0.6
0.4
0.2
0.1
jI or g
USE TOP SCALE
USE BOTTOM SCALE
Example: for g = 0.85, I = 0.76
-1
-0.5
0
0.5
1.0
1.5
2.0
log jI or log g

FIGURE 4



PROCESS NOMOGRAM – FIGURE 5

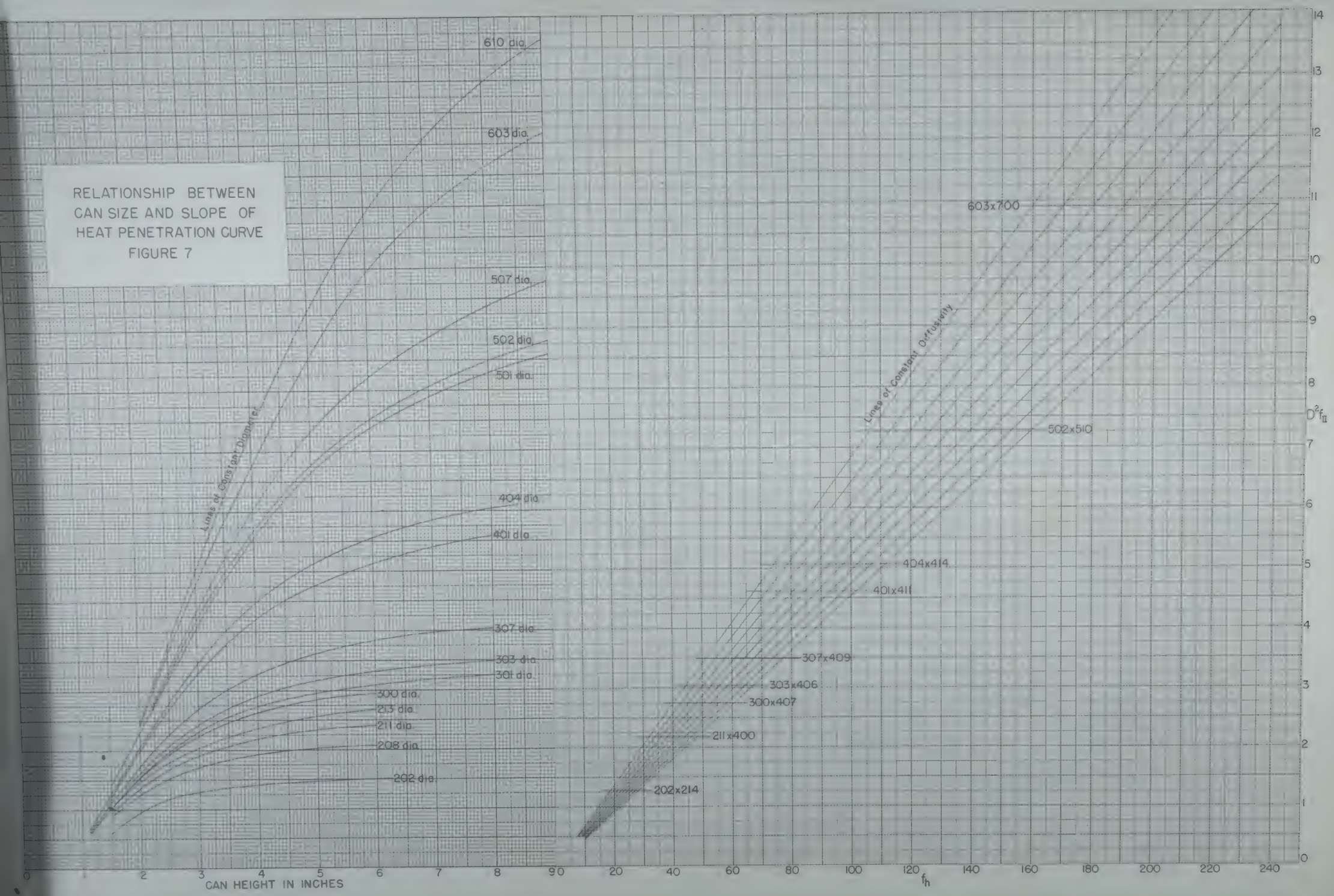


PROCESS NOMOGRAM

FIGURE 6

RELATIONSHIP BETWEEN CAN SIZE AND SLOPE OF HEAT PENETRATION CURVE

FIGURE 7



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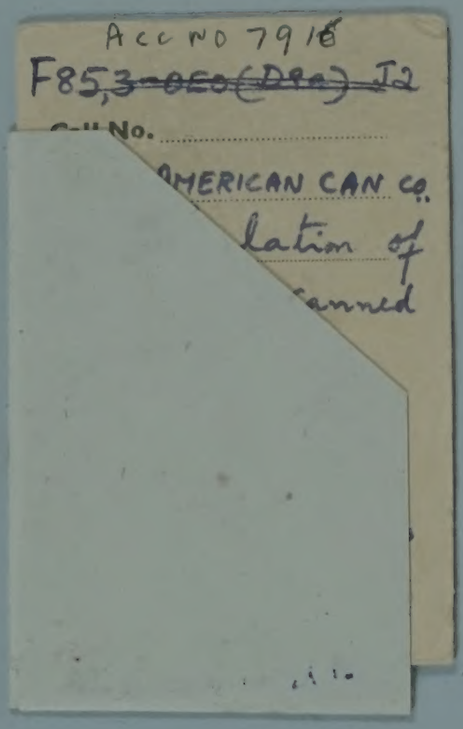

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